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Modelling the Evolution of Economic Structure and Climate Change: A Review*

Tommaso Ciarli[†] Maria Savona[‡]

Abstract

We discuss how different models assessing climate change integrate aspects of structural change that are crucial to improve understanding of the relation between changes in the environment and in the economy. We identify six related aspects of structural change, which have significant impact on climate change: sectoral composition, industrial organisation, technology, employment, final demand, and institutions. Economic models vary substantially with respect to the aspects of structural change that they include, and how they model them. We review different modelling families and compare these differences: integrated assessment models (IAM), computable general equilibrium (CGE) models, structural change models (SCM), ecological macroeconomics models in the Keynesian tradition (EMK) and evolutionary agent based models (EABM). We find that IAM and CGE address few of the aspects of structural change identified; SCM focus on the sectoral composition; and EKM study final demand and employment structure. But all these models are aggregate and omit the complexity of the interactions between structural and climate change. EABM have explored a larger number of aspects of structural change, modelling their emergence from the interaction of microeconomic actors, but have not yet exploited their potential to study the interactions among interrelated aspects of structural and climate change.

Keywords: Structural change; climate change; economic modelling

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1 Introduction

Economic growth is tightly related to several aspects of structural change, such as sectoral composition of output and value added, division of labour, technology of production, industrial organisation and competition, firm size and organisation, and demand composition and preferences.¹ Some changes precede economic growth, others unfold as a consequence of economic growth.

Most (if not all) aspects of structural change influence the short- and long-run relations between economic activity and the natural environment, in ways that are often not predictable, and which are not yet established in the literature (Savona and Ciarli, 2017).

To make things slightly more complicated, the relation is mutual, as changes in the natural environment influence several aspects of structural change (Stern, 2013).

To complicate things one step further, most different aspects of structural change are interrelated, they depend on one another (Ciarli et al., 2010, 2018). For instance, industrialisation and tertiarisation are accompanied by urbanisation (Harris and Todaro, 1970). Economic growth is associated with an increase in the division of labour (e.g. Smith, 1961; Greif, 2006), which changes the relation between industries (Input Output coefficients) and between firms, and modifies the organisation of firms and of production (Lazonick, 1979; von Tunzelmann, 1995). Changes in industries and in the division of labour modify the trade relations among countries, and countries' terms of trade (Prebisch, 1950; Singer, 1950; Hidalgo et al., 2007; Cimoli and Porcile, 2013). Sectoral and organisational changes are accompanied by radical and incremental technical changes (Freeman et al., 1982; Mokyr, 2007; Rosenberg, 1974). New and cheaper goods and services must be accompanied by changes in the demand composition (Berg, 2002; Maddison, 2003), social structure and distribution of income. We also expect changes in the organisation of production, trade, technologies, demand and income distribution, to be accompanied by changes in institutions (North, 2005; Chang, 2010; Bowles, 1998), the organisation of societies (McCloskey, 2009), labour markets and employment relations (Lazonick, 1994), and the international economic order (Galeano, 1980).

Therefore, to improve our understanding of the relation between economic growth and environmental impact, we need models that capture: the interactions between different aspects of structural change, at different levels of aggregation; and the interactions between different aspects of structural change and environmental impact (van den Bergh and Gowdy, 2000; Sassi et al., 2010). Focussing on a single aspect of structural change risks to provide a partial understanding of the impact of economic activity on the environment. For example, focussing exclusively on employment shares across industries, we may overlook the role that consumer behaviour (e.g. income, distribution and preferences) may have on these shares, and their effect on, e.g., industrial organisation, technical change, trade, transport. In turn, each of these related aspects of structural change may have a different impact on, for example, emissions.

This paper discusses how different models assessing environmental impact and climate change integrate aspects of structural change that are, we argue, crucial to improve our understanding of the relation between changes in the environment and in the economy. We consider a broad set of aspects of structural change, following Matsuyama (2008) and Saviotti and Gaffard (2008), and building upon the models by Ciarli et al. (2010)–Ciarli et al. (2018). If, as discussed above and more at length in the next section, models should include several aspects of structural change – and their relation, to provide a reliable representation of the impact of economic growth on different aspects of climate change, we assess models on the basis of the number of aspects of endogenous structural change included – and on how their interaction is modelled. Because the interaction of several aspects of structural change imply qualitative changes that cannot be captured by representing a system in equilibrium van den Bergh and Gowdy (2000); Saviotti

¹See, for example, Kuznets (1973), Berg (2002), Mokyr (2002), Ayres and van den Bergh (2005), McCloskey (2009), Desmet and Parente (2012), Ciarli et al. (2010) and Ciarli et al. (2018).

and Gaffard (2008); Balint et al. (2017) – or moving between equilibria – we find that the family of models that is best suited to capture the interactions between several aspects of structural change and climate change are evolutionary agent based models.

In earlier work, van Ruijven et al. (2008) briefly discuss the extent to which existing ‘global’ energy models deal with aspects of structural change that are relevant to developing countries. They consider a limited set of aspects of structural change, mostly related to energy, which include: the use of traditional fuels, electrification, (aggregate) sectoral change, income distribution, informal economy, and resource depletion. In an earlier review of models and their account for crucial aspects of environmental sustainability, Köhler et al. (2006a) found that the available models did not include a satisfactory understanding of technological change, particularly with respect to the diffusion of technologies, uncertainty of innovation, path dependency, and heterogeneity of agents and technologies.

We contrast a more complete set of models than van Ruijven et al. (2008), covering different modelling traditions. As in van Ruijven et al. (2008), we do not aim to be exhaustive: we include aspects of structural change that we consider relevant for both economic growth and climate change, and review a sample of models for each group of models.

The paper offers three major contributions. First, based on the empirical evidence surveyed in Savona and Ciarli (2017), we offer a rationale for addressing the complexity of the relations between different aspects of structural and climate change within a modelling framework.

Second, we single out six different aspects, each disaggregated in a number of components (Section 2). Because many of these aspects are related, we argue that they should be integrated within a unique modelling effort, to ensure a proper assessment of the impact of economic activity on the environment.

Third, we review five families of economic models that study the environmental impact of production and consumption (covering the whole population of modelling traditions that we are aware of) (Section 3): Integrated Assessment Models (IAM), Computable General Equilibrium (CGE) models, Structural Change Models (SCM), Ecological Macroeconomics models (in the Keynesian tradition) (EMK), and multi agent and evolutionary models (EABM). For each family of models we discuss the aspects of structural change that they include (endogenise), and their limitations.²

Finally, Section 4 concludes the paper.

2 Six Aspects of Structural Change and Their Relations with Climate Change

We follow Matsuyama (2008) in defining structural change as a set of interrelated aspects: “[...] complementary changes in various aspects of the economy, such as the sector compositions of output and employment, the organization of industry, the financial system, income and wealth distribution, demography, political institutions, and even the society’s value system.” Using a similar definition, (Saviotti and Gaffard, 2008, p. 115)³ suggest that it is not meaningful to model a system in equilibrium “when its composition keeps changing due to the emergence of qualitatively different entities”, including all aspects of structural change.

Drawing from those definitions we focus on six related aspects of structural change: sectoral composition, industrial organisation (IO), technical change, employment, demand, and institutions. Although one could easily identify other categorisations, this one has a number of advantages: it loosely builds on previous modelling work, all aspects are related to climate change (Savona and Ciarli, 2017), and was built bringing together related literatures.

²See Köhler et al. (2018) for a similar exercise review focusing on sustainability transitions.

³“[c]hange in the structure of the economic system, that is, in its components and in their interactions. Components are [...] particular goods or services, and other activities and institutions, such as technologies, types of knowledge, organisational forms etc.”

In what follows we discuss how different aspects of structural change may be related to climate change. Table 1 summaries the six aspects, and lists a number of components relevant to climate change for each of them. We also briefly make connections between different aspects, when the relevance of a component to climate change is related to one of the other aspects of structural change.

2.1 Sectors

The sectoral composition of an economy influences different aspects of climate change directly and indirectly, through Input Output (I/O) relations, and trade (see also Savona and Ciarli (2017) for a summary). Inputs differ in terms of technical coefficients, labour coefficients, and energy intensity. All three are influenced by other aspects of structural change, such as technical change.

Directly, industries contribute differently to greenhouse gases (GHG) emissions (Stern, 2008) and differ in terms of the cost needed to abate them Enkvist et al. (2007). Indirectly, different industries require different skill sets (Vona and Consoli, 2014), differ in terms of innovative activity (Malerba and Orsenigo, 1997) – level and composition, rents and wages, influencing the distribution of income (which has an effect on climate change through the composition of demand).

We identify five relevant components of the sectoral aspect of structural change (Table 1): sectoral composition, which affect (1) the contribution to GHG emissions; (2) the cost of abatement; (3) sectoral differences in innovative activity; (4) technical, labour, and consumption I/O coefficients; and (5) dematerialisation.

2.2 Industrial Organisation (IO)

Closely connected to changes in the sectoral composition are changes in the organisation of production through firms decision to make or buy. Changes in the organisation of production has three main direct effects on climate change. First, increased specialisation is usually associated with higher productivity, which may influence energy intensity. Second, as firms outsource part of the production, they are likely to require more transportation, which is an important component of GHG emissions. Third, outsourcing may come with increased trade, which may imply off-shoring of more or less polluting activities.

Indirectly, the organisation of production may determine market concentration and firm size. In turn, firm size has been shown to be related to the distribution of wages (Bottazzi and Grazzi, 2010; Brown and Medoff, 1989). Changes in productivity across industries may also influence the labour market. These aspects are related to the demand side aspects of structural change. Changes in the organisation of production are also likely to modify the geographic concentration of economic activities and workers, an important factor in the contribution of transportation to GHG emissions.⁴ Finally, changes in the structure of production, geographic and market concentration, and technology life cycle (Abernathy and Utterback, 1978), affect industrial dynamics (Klepper, 1997; Mazzucato, 2002).⁵

We consider five relevant components connected to the structure of production and industrial organisation, which are related to climate change (Table 1): (1) the emergence of new intermediate industries; (2) changes in I/O coefficients; (3) market concentration and firm size; (4) geographical clustering; and (5) industrial dynamics.

⁴See for example Vergara et al. (2013) and GEA (2012, p. 13).

⁵It is important to note that industry life cycles and industrial dynamics are also influenced by the technological regimes mentioned above (Malerba and Orsenigo, 1997), and have been relevant determinants in industrialisation and catching processes (Kim, 1999).

2.3 Technical change

Technical change is central both to structural and climate change (Cole et al., eds, 1973; Stern, 2008). It affects the environmental impact of production and consumption in four main ways. First, innovation leads to the substitution of capital and energy for labour, and the the increase in consumption. Second, factor saving environmental innovations (van den Bergh, 2013) may improve the energy efficiency of production processes. Third, via de-materialisation the value added of final goods can be increased, so that consumers gain the same utility from consuming less of a given material good (Ayres and van den Bergh, 2005). Third, by substituting renewable energy sources for fossil fuels (Ayres, 1998; Popp et al., 2010; Stern, 2007).

It is important to distinguish between incremental innovations, which improve energy efficiency, and radical innovations, which require changes in large parts of the economy, including consumer behaviour (below), the production structure (above), and infrastructures (Safarzyńska et al., 2012; van den Bergh et al., 2011), with unindented consequences on the environment (Windrum et al., 2009b). It is also crucial to consider that innovations cluster in time and space, they do not cumulate in a linear fashion (Silverberg and Verspagen, 2007, 2005).⁶ The relation between technical change, climate change, and structural change, is not linear: innovation takes time, requires high investments, changes incrementally, has uncertain returns (Nelson and Winter, 1982), and may have a negative impact on climate change in several intended and unintended ways. Uncertainty on the consequences on climate change applies to both ‘brown’ and ‘green’ technologies. For example the controversial impact of the cultivation of biofuels, the rebound effect (Stapleton et al., 2015; Steve Sorrell, 2007) and the green paradox (van der Ploeg, 2011; van der Ploeg and Withagen, 2012). Innovation may follow different directions, all with different advantages and disadvantages for the environment (Leach et al., 2010; Stirling, 2009). The direction chosen depends also on the structural institutional aspect of the economy.

We consider seven relevant components that tie technical change to climate change (Table 1): (1) factor bias; (2) clean technologies/energy; (3) radical innovations and changes in paradigms and trajectories; (4) non linear and clustered dynamics; and (7) uncertainties and unintended effects.

[TABLE 1 HERE]

2.4 Employment

Production structure, firm organisation and technologies influence also employment and its compensation.⁷ For instance, employment relocates across industries and geography, and the new industries and technologies demand for new skills and novel combinations of know-how (Vona and Consoli, 2014; Consoli et al., 2016). The pace of adaptation of the labour market to new industries, geographies, technologies and tasks, may induce a more or less efficient transition towards green technologies – or impede it.

Indirectly, changes in employment are likely to affect the distribution of wages (Brynjolfsson and McAfee, 2014), which has an important effect on the demand composition (more below).

We consider five components of the employment aspect of structural change, which are related to climate change (Table 1): (1) green jobs and changes in the skill sets; (2) unemployment; (3) distribution of wages; (4) changes in the labour intensity across industries; and (5) labour composition across industries.

⁶This dynamics can also be interpreted through the lenses of long waves (Freeman et al., 1982), particularly if we consider that the latest of these waves may be around environmentally friendly technologies (Freeman, 1996), and socio-technical transitions (Köhler, 2012).

⁷The implications of a green transformation for the job market are still not well understood, due to the multiple compensation effects (Dierdorff et al., 2009; IEA, 2009; Martinez-Fernandez et al., 2010).

2.5 Demand

On the demand side there are two main aspects of structural change that are crucial to climate change, and which are related to aspects discussed above.

First, income distribution.⁸ Income distribution shapes the level of final consumption through savings (Dynan et al., 2004), the distribution of consumption across industries (Aguilar and Bils, 2015),⁹ aversion to pollution (Greenstone and Jack, 2015) and a country’s capacity to generate environmental innovations (Vona and Patriarca, 2011).

Second, and related, consumer preferences change with income and over time (Witt, 2001, 2011). They can create an incentive to innovate towards greener, or cheaper goods (Janssen and Jager, 2002; Windrum et al., 2009a,b). Preferences have been discussed extensively with respect to time: risk aversion and the rate at which individuals discount future generations’ consumption and cost of climate change, relative to present consumption and costs to reduce emission Stern (2013); Pindyck (2013); Nordhaus (2013).

We consider three broad components related the demand aspect of structural change (Table 1): (1) income distribution; (2) consumption preferences; and (3) preferences for direct and indirect effects of environmental degradation, current and future.

2.6 Institutions

Several components of the aspects of structural change just discussed are influenced by institutions shaping policies (Arrow et al., 1995), incentives, social structures, and interactions (Arrow et al., 1995; Boulanger and Bréchet, 2005; Greenstone and Jack, 2015; Fagerberg et al., 2016).

Innovation systems can help identify the main institutional weaknesses in harnessing environmentally friendly technology Jacobsson and Bergek (2011). As discussed with respect to technological trajectories and pathways, agency and power are crucial in determining the transition towards more environmentally friendly socio-technical regimes (Smith et al., 2005; van den Bergh et al., 2011).

Because of the complexity of defining, measuring and stylising institutions, they are also the most problematic aspect to model. We consider the following components of the institutional aspect of structural change related to climate change (Table 1): (1) appropriation regimes and property rights; (2) technological opportunities; (3) access to resources (power relations); (4) governance (power relations); and (5) social interactions.

3 A Review of Economic Models

In this section we briefly discuss how the main modelling traditions that investigate the relation between the economy and climate change include one or more of the aspects structural change. We review, in turn, IAM and CGE models (Section 3.1), models that focus on sectoral change and build on the structuralist tradition in economics (Chenery et al., 1984; Palma, 2008), which we call structural change models (SCM) (Section 3.2), the recent ecological macroeconomic models in the Post Keynesian tradition (EMK) (Section 3.3),¹⁰ and evolutionary agent based models (EABM) (3.4).

For each modelling tradition, we briefly summarise the main features of the models.¹¹ We

⁸E.g. related to the organisation of production and firm size (Ciarli et al., 2010), off-shoring of part of the production, distribution of skills (Consoli et al., 2016), and investment in (green) capital and the distribution of its rents (Rezai et al., 2013).

⁹Which can be more or less polluting.

¹⁰We do not consider econometric approaches which combine I/O and post Keynesian features, such as E3MG (Köhler et al., 2006b) or FIDELIO (Kratena et al., 2013), because they are developed mainly for estimation purposes.

¹¹For reasons of space we do no proper justice to any of the models, especially for IAM and CGE models for which a large number have been produced and assessed (and for which a large number of excellent reviews exist).

then discuss how these models account (or not) for the six aspects of structural change. A sketched summary of this discussion for all models is presented in Table 2. Table 3 provides a more detailed check-list of which of the components discussed in Section 2, and listed in Table 1 is included in the different classes of models.

3.1 Integrated Assessment Models (IAM) and Computable General Equilibrium (CGE) Models

3.1.1 IAM

Since Nordhaus (1979), a large number of IAM have been developed to study the impact of economic activity on climate change, and the economic costs of reducing the environmental impact of production and consumption.¹²

Stern (2008) and Pindyck (2013) summarises the linear cycle stylised in IAM between the environment, social and economic factors in the following 6 steps: (1) consumption and production decisions generate GHG; (2) the GHG flow is transformed in a stock accumulated in the atmosphere; (3) this stock traps heat and generates global warming at a given rate; (4) warming induces climate change; and (5) climate change has several effects on individuals and the environment (damage function), which are quite complex to capture and assess; (6) GHG flow and stocks may be abated with a given cost which depends on present and future costs of climate change, the present cost of abating GHG emissions, and time preferences.

Despite their great contribution in understanding some of the relations between present economic activity, environmental impact, and its costs on future economic activities, IAM have a number of limitations that need to be addressed before they can become a reliable tool to assess policies for sustainable growth (Stern, 2013; Pindyck, 2013; Stern, 2016). In particular: (1) the drivers of growth are exogenous, unaffected by climate change – climate change may have permanent effects on the stock of capital; (2) there is no account of radical uncertainty (Weitzman, 2011, 2009, 2014); (3) few IAM consider probability distributions of risks; (4) the assumptions about social welfare based on the estimation of the risk aversion to future changes, and of the discount rate; (5) limited attention to technological change which may reduce the costs of future mitigations via the use of renewable resources, or reduce the use of energy (Ackerman et al., 2009).¹³

In recent reviews, Farmer et al. (2015), Mercure et al. (2016), and Balint et al. (2017) discuss more substantive limitations, with respect to the complexity of climate change, its relations with the real and the financial economy, and the relevance of incorporating the interactions between different economic agents.

Aspects and Components of Structural Change

The extent to which IAM capture different aspects of structural change is limited (Tables 2 and 3). First, they account for limited differences across macro sectors of the economy, at an aggregate level, distinguishing only between sources of energy use. The cost of reducing GHG emissions depends on the industrial composition, and its use of resources (e.g. transport and energy efficiency, and land use) (Stern, 2008), but the relative growth of different industries and macro sectors is not endogenised and I/O relations do not change.

Second, when endogenised, technical change is modelled as a linear learning by doing (LBD) or by an aggregate R&D function (see Popp (2004) and reviews in Köhler et al. (2006a), Gillingham et al. (2008), and Popp et al. (2010)). Because these changes occur at the margin (Ackerman et al., 2009), they normally represent a reduction in the energy use but have no effect on the structure of the economy.

¹²Wei et al. (2015) perform a basic bibliometric exercise that describes the extent and distribution of research on IAM.

¹³See Farmer et al. (2015) for a short discussion of technological change in IAM.

Third, IAM assume full employment, and changes in wage, skills, or (green) jobs are not considered, to our knowledge.

Fourth, on the demand side IAM include time preferences of the representative agent, which in more sophisticated models change with the impact of GHG. Although time preferences are a relevant aspect of consumption related structural change that a model should consider, they are likely to depend on other state variables as well, such as income, not included in IAMs.

Finally, no endogenous changes in the rules, regulations, or distribution of power is considered in IAM. Policies are introduced exogenously, and used to contrast their effect on costs and benefits of abatement.

3.1.2 CGE

A large number of CGE model have been adapted to run integrated assessment in a framework of multiple macro sectors in equilibrium (market is cleared in each period) (Boulangier and Bréchet, 2005). These are complex models with a large number of regions and industries, connected to the environment through the use of various energy sources and GHG emissions. Figure 1 depicts the three main markets of a typical CGE: labour, capital, and goods.

[FIGURE 1 HERE]

Figure 2 shows an example of the full structure of a CGE model with several economies, industries, and energy inputs. Policy instruments addressing the incentives for different macro sectors of the economy (such as taxes) are assessed with a number of environmental indicators.

[FIGURE 2 HERE]

A standard CGE is composed of three main groups of agents: households, firms, and the government, plus the rest of the world (RoW in Figure 1).¹⁴ Households pertain to different economic groups, but each group is composed by a representative household maximising an inter-temporal utility function to find the optimal combination of savings and consumption. Households buy from different industries durable and non durable goods, produced domestically or imported. Households' budget constraint is determined by their wages (via the labour market equilibrium), savings, taxes, and transfers. The sources of energy consumption for households are: fuel for transport, electricity and heating. To account for the rebound effect, energy is a nominal service the demand of which depends on service prices (for more energy efficiency, a lower price would command a higher demand).

Firms maximise profits, subject to the available capital stock and technology, using labour,¹⁵ capital, intermediate inputs, and energy sources. Models may differ with respect to the energy sources included, how they are converted in energy use and how these are converted into GHG emissions. Models usually have one representative firm per industry. Input quantities depend on factors demand, which depend on their prices. Capital, labour, and energy prices are usually determined exogenously. Technical change is modelled for each input individually, modifying the composition of inputs (factor biased), and as a change in Total Factor Productivity (TFP). Technical change is usually semi endogenous, mainly driven by LBD. The model dynamics is a result of investment in new capital (through savings).

In the labour market, households and firms bargain the number of working hours – depending on the amount of leisure that households want to consume in the present and in the future, determining the equilibrium wages (using efficiency wages). Voluntary unemployment is then determined by the choice of households and market frictions. Labour supply may change with population characteristics, which evolve exogenously.

¹⁴We follow Capros et al. (2013).

¹⁵Which may be divided between skilled and unskilled.

The I/O coefficient define the flow of goods and money between industries, including a number of intermediate industries, final demand for durable and non durable goods, imports, and exports.

The models are closed by the public sector collecting taxes and paying benefits (mainly to unemployed) and interests.

CGE models are calibrated with data on consumption, industries, investment, wages, trade, taxes and transfers, I/O coefficients, and GHG emissions. Models are then simulated for a number of periods to assess the environmental outcome, in equilibrium, for different policies that affect households', firms' and government's objective function.

Aspects and Components of Structural Change

The extent to which CGE capture aspects of structural change and their interaction improves with respect to IAM, but is still limited (Tables 2 and 3).

First, these are multi-sector models. The contribution of each industry to output is given by calibrated I/O coefficients. However, changes in the division of labour is not contemplated and I/O coefficients are fixed through time. (with the exception of some models introducing a semi exogenous LBD).

Second and related, different industries contribute differently to GHG emissions, and may be produced domestically or imported, but the only endogenous change in the intermediate demand, is due to LBD or continuous and monotonous directed technological change.¹⁶

Technical change, therefore, is modelled in a way similar to IAM: changes occur at the margin, as improvements in energy efficiency or GHG emissions.

Fourth, on the demand side different groups of households have different incomes, and may have different preferences for goods' prices. But these preferences do not change with time, satiation, or emergence of new goods (no new goods emerge). Consumption patterns change as a function of income, representing a relevant aspect of structural change. When changes in labour markets and urbanisation are included in CGE, they are considered as exogenous, such as in O'Neill et al. (2012).

Alike IAM, CGE models account for institutions as exogenous policies that may be implemented to reduce GHG emissions. No institutional aspect is represented.¹⁷

[TABLE 2 HERE]

3.2 Structural Change Models (SCM)

In this section we group a number of models that explicitly investigate structural change as change in the employment shares across industries, and which are influenced by the structuralist tradition in economics (Chenery et al., 1984; Palma, 2008). Unlike IAM and CGE models, we could find a limited number of relatively different SCM. To capture these differences, we briefly discuss the main features related to aspects of structural change and climate change for a sample of models.

Campiglio (2014) models a representative household consuming a green service and a standard good, which requires to use also a common resource, the environment. The standard good benefits from the public investment in infrastructures, whereas the green service does not. Results suggest that structural change towards the green service occurs only when households

¹⁶One exception is Sassi et al. (2010), who use a fixed coefficient production function, and model changes in final uses of energy and transportation. Bosetti et al. (2009) include radical innovations in the WITCH model, but this is the outcome of linear research and development and learning effort at the aggregate level, with *ad hoc* timing and pricing.

¹⁷This is a limitation that may impossible to address within CGE models, which rest on the assumptions that market can always clear, and therefore there is no need for other institutions to regulate them, or an economy more at wide (Scricciu, 2007).

have a lower preference for the manufacturing good, or when the ratio of public versus private investment is larger than the long run equilibrium level. Higher rates of public investment have a negative effect on welfare because they increase private capital reducing the common resource (environment).

Antoci et al. (2012) study how the dynamics of sustainability in developing countries is affected by changes in the sectoral composition, in the presence of natural resources that can be exploited by different agents, and put to different uses. Their model represents a small open economy with two industries, a traditional industry based on the use of natural resources, and a manufacturing industry (with a representative firm for each industry). Both industries use natural resources to produce output. The main difference is that the traditional industry cannot substitute machines for natural capital, while this is possible in manufacturing. The model has two different agents: the ‘poor’, who depend on self employment using natural resources, or who are employed by the ‘rich’; and the ‘rich’, who invest in new capital. Structural change involves the poor agents only. They can either remain in the traditional industry, using the natural resource, or work in the modern industry, for a salary. This can occur only because of exogenous changes: (1) increase in the productivity of the modern industry; (2) increase in the environmental impact of either industry; (3) reduction in the carrying capacity of the natural resource (availability).

Both models address and illustrate two interesting aspects of structural change and environmental impact, respectively related to tertiarisation and the exploitation of natural resources, but do not provide further elements *on* the modelling of endogenous structural change.

Pasche (2002) proposes a stylised model of sectoral change that follows an evolutionary process, showing that technological and sectoral change have only a short run effect on the reduction of emissions. To abate pollution in the long run the economy has to converge either to lower consumption or to zero growth. Bretschger and Smulders (2012) consider the effect of both sectoral change and innovation on the use of resources in a model in which workers can move across industries with different rates of innovation. Contrary to Pasche (2002), they find that structural change can complement technological change in achieving sustainability, even when there is no alternative to non-renewable resources to produce energy (low substitutability between renewable and non-renewable sources of energy). The use of natural resources for producing energy pushes structural change, which together with innovation in the different industries allows the economy to keep growing. van der Meijden and Smulders (2018) find that the availability of renewable technologies provide an incentive for more R&D and investment, contributing to growth and to the transition from non renewable to renewable sources of energy. Their results are in contradiction with models assuming that the reduction in the availability of energy sources should reduce incentives to innovate and invest in other activities (due to the difference in prices).

Pan (2006) extends the analysis to more than two industries, vertically integrated, and introduces technical change in the I/O coefficients. New technologies are the result of endogenous technical change through investment in a dynamic I/O model. The model is quite aggregate and assumes a stylised dynamic of technical change, but it is an important step towards considering two fundamental and related aspects of structural change: technological change and the organisation of production.

Ayres and van den Bergh (2005) introduce further aspects of structural change and their relation with environmental impact. Focussing on the substitution of production factors, they identify three main steps of endogenous growth that allow to sustain exponential growth. First, changes in inputs and LBD (use of fossil fuel resources). As fossil fuels substitute human energy, they increase productivity, save time and labour, reduce prices, increase demand and induce more use of fossil fuels, reducing its costs via learning (a simplification of technological change). Second, industrial organisation and final demand (division of labour and learning). Vertical specialisation increases productivity, through technological change, economies of scale

and LBD, reducing prices and increasing consumption. The increase in consumption has to be accompanied by product innovations that push upwards Engel curves. Third, radical innovation and demand (de-materialisation). This mechanism operates through an increase in the value added of final goods, so that the number of goods produced can decrease, moving to services that replace them. In order to generate sustained endogenous growth the new services must command new demand.

Aspects and Components of Structural Change

Most SCM focus on sectors (employment composition) and demand components of structural change (see also Tables 2 and 3). Most are two sectors models (polluting and non polluting) where changes in the allocation of labour across sectors depends on output cost, which depends on scarcity or the negative externalities it generates and on exogenous factors such as technological change and policies.

A couple of models also introduce industrial organisation, such as changes in the I/O structure (Pan, 2006), and technical change in the form of radical innovation, such as the emergence of new intermediate industries leading to de-materialisation (Ayres and van den Bergh, 2005).¹⁸

With respect to employment, these models focus only on sector shares (labour composition), which in a couple of models may imply changes in income. Changes on the demand side are contemplated only in Antoci et al. (2012) (income distribution between two classes of consumers) and Ayres and van den Bergh (2005) (satiation which leads to technical change).

Endogenous changes in institutions, as for IAM and CGE models, are not contemplated, but are used to study alternative scenarios.

3.3 Ecological Macroeconomics (Post Keynesian) (EMK)

A number of recent papers integrate ecological issues (biophysical limits) and post-Keynesian macro models (macro balance constraints and demand driven) in what has been called ecological macroeconomics (Jackson, 2009; Jackson et al., 2014; Rezai et al., 2013; Rezai and Stagl, 2016).

Hardt and O'Neill (2017) summarise their main features in a recent review. Models tend to include the following six macro sectors related through monetary transactions: households, firms, banks, government, central bank and the 'rest of the world' (Jackson et al., 2016). An increasing number of these models model these relations in a stock flow consistent (SFC) framework (Lavoie and Godley, 2001), which echoes the stock and flow constraints characterising natural resources, and which allows to model the relation between environmental instability and financial instability in the economy (as part of the damage function). Models do not assume full employment, allowing to study the relation between environmental constraints, negative growth rates, and consequences on the real economy. Some of the models are multi-industry and include I/O relations similar to those discussed for CGE models (inputs requirements are assumed constant), and industry-specific emissions. Figure 3 shows an example of one of the richest EMK model, which is multi-industry, SFC, includes different energy sources, and three classes of households (capitalists, workers, and unemployed).

[FIGURE 3 HERE]

The environmental damage is usually modelled exploiting the multi-industry I/O structure together with the differentiated sectoral impacts, or by assuming different energy sources. Only a small number of models integrate the feedback from the environmental degradation to macro economic outcome.

The main contributions of these models are the inclusion of financial balances, to account for the relation between financial and environmental instabilities, and (aggregate) employment

¹⁸With respect to technical change, Pan (2006) does not go much beyond exogenous dynamics and the already discussed factor saving learning curves and innovations.

dynamics. Stock flow consistent models are useful to study how indebtedness in some macro sectors of the economy (firms, households, banks) may impact on other macro sectors, and defines constraint in the economic system (households demand and investment behaviour) that are similar to those in the environment. The attention to employment makes it possible to focus on the relation between changes in productivity, wages, and working hours, for example in the context of reducing output and employment to reduce the impact on the environment. For instance, Rezai et al. (2013) argue that reducing working hours may have counter-intuitive effects at the aggregate level, by tightening the labour market, increasing workers' bargaining power, and increasing wages, which may provide an incentive for firms to increase capital investment and productivity. This, in turn might have a negative effect on climate change (increasing energy use), ambiguous effects on unemployment, and increases capital output. Rezai et al. (2013) also warns against a shift towards more productive industries, which may also have undesired effects: cross country estimates show that the increase in productivity is related to increases in energy use (60%) and only partially to an increase in energy efficiency. In other words, energy efficiency alone can mitigate only partially the ecological impacts of increases in output. One of the reasons for this is the existence of a rebound effect also at the macro level in a framework in which there is non voluntary unemployment. This is explained by an increase in expenditure in green technologies to increase energy efficiency, which would also increase output and therefore energy consumption (independent of households income and energy price, which is the rebound effect at the micro level).

Related to employment, some EMK models integrate the functional distribution of income, with some models distinguish capitalists and wage earners (e.g. Figure 3). However, no other differences in income are considered, and classes' population does not change. Jackson et al. (2014) propose to include income distribution in EMK models, for example to test if lower growth increases the capital share of an economy, inducing more inequality, use of energy, and of natural resources.¹⁹ But so far this remains in the agenda.

Aspects and Components of Structural Change

Rezai et al. (2013) suggest that EMK models can address some of the preoccupations of ecological economists, such as adaptive and bounded rational behaviour, income distribution, macro rebound effects, and de-growth scenarios (reduced consumption) which may lead to unemployment (see also Tables 2 and 3).

They account for short run disequilibria (and feedback loops in the case of system dynamic models (Jackson et al., 2016)), which characterise structural change. However, EMK models account for a limited number of components of structural change. With respect to employment, they include unemployment consequences of investment decisions, in some cases across different industries. With respect to industries, they endogenise changes in the environmental impact of economic activity through investment decisions that depend on the financial accounts of the economy. Similarly, the final demand may change following households indebtedness and financial instability, but they considered mainly aggregate demand, at most divided into two classes.

Less developed, so far, are changes in I/O relations between industries,²⁰ the industrial organisation, including different sources of energy, and technical change, which is totally missing – not necessarily by chance (Rezai and Stagl, 2016).

Similarly to earlier models, there is no reference to institutions, except from exogenous policies and scenarios, and non-voluntary unemployment.

¹⁹Jackson and Victor (2016) show that this is not necessarily the case.

²⁰A more focussed contribution, Kemp-Benedict (2014) builds a neo-ricardian model to study the role of primary resources on economic growth. The model represents three vertically integrated industries, whose contribution to growth is measured by a mark-up on the cost of external inputs, to analyse how changes in the demand have different effects on primary, circulating and wage components.

While promising, the current state of modelling in EMK models/proposals does not offer many more elements to account for structural change than those presented in advanced CGE models and SCM, a part from employment and investment instability.

3.4 Evolutionary Agent Based Models (EABM)

It is unlikely that modifications to the aggregate models discussed so far (including micro-founded models relying on the representative agent, such as CGE) may add substantial aspects and components of structural change, and their interactions with climate change. This is because most aspects depend on the interactions within and between populations of heterogeneous agents, and how these interactions change over time and under internal and external pressures Farmer et al. (2015).

To properly examine the relation between economic activity and the natural environment we would benefit from models that (van den Bergh and Gowdy, 2000): 1) consider competing and mutating states of the economy, rather than a single optimal state; 2) allow for irreversibility – any economic action has an impact on the system, not a mere experiment that can be retracted; 3) depart from marginal variations, because changes in species and components of structural change have multiple impacts whose interactions is not possible to predict from a single function;²¹ 4) include threshold effects – systems may reach tipping points that induce radical changes, which are usually not reversible; 5) include evolutionary processes of selection, mutation (innovation) and retention, which explain both ecological and economic dynamics (Nelson and Winter, 1982).

Evolutionary economics has studied some of the aspects of structural change discussed in this paper, modelling the co-evolution of traits (e.g. preferences), agents and populations at different levels (e.g. workers and firms), the emergence of new activities and the transition to new technologies. Agent Based Models (ABM) have been successfully used to study (Balint et al., 2017) out-of-equilibrium dynamics, crises and tipping points emerging from the interaction between several heterogeneous agents; they integrated agents that adapt, mutate, form preferences, reproduce, and influence other agents' preferences and behaviour in a way that is not predictable looking at the behaviour of the single entity (Arthur, 2013), or directly at the aggregates (Beinhocker, 2006; Tesfatsion and Judd, eds, 2006).²²

We focus on macro models that represent the whole economy, because they are comparable to models discussed so far. Due to the substantial differences in modelling strategies, we summarise the main features related to aspects of structural change for a number of models. Unless differently specified, all models are micro based, and study macroeconomic dynamics as an emerging property of interactions among agents and populations (Tsfatsion and Judd, eds, 2006). We briefly summarise micro models that focus on specific macro sectors of the economy at the end.

Wolf et al. (2013) (Lagom RegiO), based on Mandel et al. (2010), embody several aspects of structural change. Sectoral composition may change through time, as a result of technological change and demand composition, influencing the contribution to GHG emissions. I/O relations between industries may also change as a result of innovation and imitation. Changes in IO include industrial dynamics and the distribution of firms' size. These are result of induced technical change and LBD, incorporating structural process such as the emergence of radical innovations and technology clustering (through imitation). The model also includes related

²¹For instance, it is impossible to compute the value (or the effect) of one species that goes missing: species are interconnected in a complex system, and it is not always possible to assess what happens to the rest of the system when they mutate.

²²Further discussion on the comparison between models in the neoclassical tradition and agent based and evolutionary models see Scricciu et al. (2013) and Giupponi et al. (2013). For a broader discussion on the major differences between multi agent models and CGE models, in particular DSGE models, see Fagiolo and Roventini (2012).

changes in employment and final demand. Households look for jobs in their and neighbouring regions (migration). Labour supply and innovation (when labour saving), together with labour demand across regions determine unemployment and wages, affecting income distribution. Other components of structural change on the demand side include household imitation of their neighbours, which changes the aggregate composition of demand across firms and industries. The environmental impact simply depends on the fuel used for production, which differs across industries, and has no feedbacks on the economy.

Gerst et al. (2013) (ENGAGE) based on Dosi et al. (2010), accounts for aspects of structural change mainly related to firm innovation in the capital good and the energy industries. Capital good firms produce capital vintages used by final good firms, and define a number of features for the rest of the economy: (1) the productivity of final good firms; (2) the energy required to produce the final good; (3) the energy required to produce the capital good; and (4) the energy intensity of final goods, which affects firms' market shares, their prices, and therefore the distribution of final goods with different energy intensities in the market. Emissions depend on capital vintages (technical change) and the type of energy produced. The energy industry includes firms producing energy and firms producing the technology to produce energy. Energy producers buy technologies from the technology producers, and each technology has a different price, productivity, and environmental impact. There are three technologies that can be produced: carbon heavy, carbon light, and carbon free (renewable). The substitution of cleaner technologies for more polluting ones is based on earlier models (Grübler et al., 1999; Ma and Nakamori, 2009; Robalino and Lempert, 2000). Other changes in industrial organisation include firm size and market concentration. Another important component related to technical change is the uncertainty of the innovation process, which depends on firm sales and the investment in clean energy, endogenous to firm behaviour. Energy intensity also changes the cost of consuming goods, and households' choice.

Desmarchelier and Gallouj (2012), also built on Dosi et al. (2010), study the relation between technical change, dematerialisation and changes in consumption patterns. Similarly to some SCM, they model changes in the sectoral composition of output from manufacturing to services, characterised by different GHG emissions. Structural change in sectoral composition is related to changes in employment (between the two industries) and consumption shares of heterogeneous consumers which evolves over time following Engel curves which are functions of wages (which also differ across the two industries): as wages increase, households substitute manufacturing goods for services. Technical change occurs mainly as changes in capital vintages, induced by a tax on emissions which puts a selection pressure on more polluting firms.

Monasterolo and Raberto (2016) is an interesting mix of macro system dynamics (as in some EMK models) and agent based modelling, and can represent an interesting bridge between the two traditions. They study the effect of green fiscal policies and monetary policies on firms' investments, unemployment, wages, credit market and economic growth. They account for aspects of structural change related to employment and demand through income distribution. They model the relation between technology and (green) skills, which has an effect on the distribution of wages. The model also represents two classes of consumers. Income distribution is related to green investment through the equity shares owned by the capitalists.

Lamperti et al. (2017), also based on Dosi et al. (2010), is the first ABM (we know of) that introduces an explicit damage function, providing a fully fledged ABM alternative to IAM and CGE models. The main, crucial, new aspect of structural change, with respect to models discussed so far, is the feedback impact of climate change on the structure of the economy via GHG induced shocks. From an EABM perspective, environmental shocks may change the structure of the economy because their impact may vary across populations and between agents within populations (agents are exposed to a different extent or may be more or less resilient). For instance, climate shocks may change the composition of industries, as their impact on firms' labour productivity, energy efficiency, capital stock, and inventories differs across industries.

Ponta et al. (2018), based on the EURACE model (Cincotti et al., 2010; Teglio et al., 2017), study the transition from fossil fuels to renewable energy. The main addition with respect to earlier EABM is related to sectoral composition and IO. They introduce a foreign provider of oil, which affects the cost of intermediate and final goods (through the fossil fuel energy source).

Nannen and van den Bergh (2010), based on Nordhaus (1992), is the only EABM (to our knowledge) that considers components of structural change related to institutions. The model represents different countries that decide whether to invest in more or less polluting technologies. Countries' decision evolves through time via mutation and imitation. Imitation occurs by observing the performance of neighbours' adoption choice in the past. However, countries make errors in imitating (because of limited information). Policy makers can use these errors to induce agents to invest in one or the other technology.²³ They cover three relevant components related to institutions: changes in the structure of production due to changes in the technologies (also covered by the models above), path dependency due to network externalities, and the effect of social interactions, a crucial component aspect of the institutional aspect of structural change.

3.4.1 Innovation Models (Micro)

Several EABM offer insights on the complex relations between technological change and climate change (see also Balint et al. (2017)), focussing on specific micro aspects, while ignoring the rest of the macro economy. They provide a good understanding of the incentives and behaviour of firms, consumers and other actors, and how they may contribute to radical innovations that accompany environmentally friendly transitions. Several of these models were reviewed in Safarzyńska et al. (2012).²⁴ We briefly discuss the main aspects of structural change that they study.

Oltra and Saint Jean (2009) study the relation between industrial organisation and demand components focussing on how technological regimes and demand conditions influence industrial dynamics and the consequent emergence (or lack of it) of technological designs with environmental features.

On technical change, Zeppini and van den Bergh (2011) study the emergence of radically new technologies from the recombination of existing technological trajectories that are close substitute – clean and dirty – which may lead to ‘hybrid’ technological pathways. Windrum et al. (2009b,a) use an NK model (Kauffman and Levin, 1987) to study the relation between technological complexity, demand preferences, and the emergence of radically new technologies.

Several models have studied the co-evolution of technologies consumer preferences on the demand side. Windrum et al. (2009b,a) study consumers' influence in creating incentives to invest in green technologies, and how this influence depends on income distribution, peer pressure, and firms' strategy in attracting consumers with non green product features. Safarzyńska and van den Bergh (2010a) extend that model to analyse policies on the supply (tax) and demand side (campaigns promoting green technologies). Buenstorf and Cordes (2008) analyse the role of consumers learning on the diffusion of green technologies. And Bleda and Valente (2009) study the role of eco-labelling on consumer demand and firm innovative behaviour.

Institutional components of structural change are less regarded also in micro models. Safarzyńska and van den Bergh (2010b) study the role of institutional changes on the use of natural resources and on the implementation of environmental policies. In a multilevel model of group

²³Janssen and de Vries (1998) find similar results adding agents with different views of the world to a standard aggregate model. The different views affect the way in which changes in the environmental impact are perceived, and affect the response to environmental policies. As agents learn from each other, and the share of the population with different views changes, the response to environmental policies is also affected.

²⁴Cecere et al. (2014) provide another review of green innovations from an evolutionary perspective, referring to both empirical and theoretical studies, and focussing mainly on the role of path dependency and lock-in. While Faber and Frenken (2009) is an interesting collection of evolutionary models targeting environmental economics, innovation, and policies.

selection they investigate how different forms of power modify the pay-offs distribution for different groups, and their influence in determining the future behaviour of the economy (and related ecological choices).

Aspects and Components of Structural Change

EABM relax three basic assumptions of the models discussed earlier (Sections 3.1-3.3): aggregate behaviour (or average behaviour in the case of microfoundations in CGE models), perfect rationality of heterogeneous interacting agents and out of equilibrium dynamics.²⁵ As a result, they provide insights on the relation between several aspects of structural change – in the populations, the state of the system (not necessarily in equilibrium), more or less radical technologies, non reversible technological structures – and climate change.

At the sectoral level, we have discussed models that study changes in the sectoral composition (each industry with different contributions to GHG emissions) via innovation and I/O coefficients.

With respect to IO, models introduce industrial dynamics and changes in firm size, and to a limited extent changing composition of energy sources, and geographical concentration.

The most detailed aspect of structural change is technical change, with models endogenising research of cleaner technologies through R&D, and some models introducing radical innovations, non linear, clustered and random features of innovation, and the uncertainty related to the discovery of new technologies.

With respect to employment, EABM have endogenised labour markets, unemployment, wage differences, green skills and industries with different labour intensities.

The demand side aspects of structural change have also been introduced, endogenising income distribution, and its impact on consumer preferences (which change via imitation and mutation) and consumption shares.

EABM have also integrated, although only partially, relevant institutional elements of structural change, focussing on the structure of interactions among decision makers.

More recently EABM have also introduced the reverse effect of climate change on some components of structural change through diversified shocks on different sectors of the economy.

Some of the microeconomic aspects of structural change have been developed more exhaustively in micro models that focus on environmental innovations and technological transitions. These are industrial organisation, technical change, demand, and institutions. However, these models lack the feedback with the other macro sectors of the economy.

[TABLE 3 HERE]

4 Discussion and Concluding Remarks

In order to improve our understanding of the relation between economic growth and environmental impact, we propose that it is crucial to understand the interactions between several aspects of structural change that accompany economic growth, and climate change. In Savona and Ciarli (2017) we discuss more at length the empirical evidence on some of the aspects of structural change. Assuming away these aspects of structural change in macro and policy models may lead to wrong outcomes and predictions. For example, how do changes in the composition

²⁵The extension to multiple equilibria (Wolf et al., 2016) is marginal improvement with respect to the analysis of the interaction between different aspects of structural change and climate change. Structural change, as discussed in this paper, refers to continuous processes from relatively stable conditions in the short term to different relatively stable conditions. Multiple optimal equilibria offer different potential outcomes, but does not improve our understanding of how interacting aspects of structural change move the system from one potential equilibrium to the next (which may well cease to exist during the transition process).

of industry relate to changes in firm size, employment, wages, income distribution, and therefore on consumption preferences? Because different industries have a different impact on GHG, consumers purchase different goods, demand changes with income distribution, all these aspects will matter for GHG. Because they influence one-another, modelling their interaction is crucial.

We found that different modelling traditions include aspects of structural change, their interactions, and the interactions with climate change to different degrees (Tables 2 and 3).

IAM account for some sectoral differences, distinguishing between sources of energy use, but the relative growth of these sectors is not endogenised; industrial organisation is not relevant; technical change is modelled as marginal changes in an aggregate production function through LBD; and the main changes in the demand are time preferences.

CGE models include a larger number of industries, related through I/O coefficients, with different learning curves and contributions to emissions, but these relations are fixed; they also include different consumption patterns the average representative consumer, which also does not change.

These models allow to analyse the effect of different sectoral compositions, relations, and consumption preferences, but cannot integrate structural change as part of the model dynamics. Three main assumptions make their use problematic to account for more, relevant, components of structural change (and their relation with climate change). First, perfect rationality (even under limited information) does not allow for true uncertainty, which characterise the impact of economic activities on the environment, sometimes in the form of unintended consequences. Second, in the absence of a distribution of agents, with different characteristics, preferences, and behaviours, which influence each-other, and with different influence on the system, there is no scope for structural change. Third, under the market clearing framework in which there is one unique equilibrium along which an economy grows it is not possible to capture “the emergence of qualitatively different entities” (Saviotti and Gaffard, 2008, p. 115). Even with multiple equilibria, it is not possible to model the transitional adjustments (Barker, 2004) that are at the core of structural change.²⁶

SCM focus on the I/O interaction between industries, and how they may change due to climate change. However, we found only a couple of models that introduce also changes in the I/O coefficients and model the emergence of new intermediate industries. Differences on the demand side are not more sophisticated than those already included in CGE models.

EMK models integrate ecological unbalances and monetary unbalances in a unique macroeconomic frameworks, to study the relations between ecological and macro economic balance constraints. Although models are demand driven, there is no structural change on the demand side. The main contribution is in the analysis of the nexus between (un)employment dynamics, investment, environmental impact and economic growth.

To account for related aspects of structural change, and their interactions with climate change, we need to model evolving complex systems (Costanza et al., 1993). We must represent systems that are out of equilibrium, and subject to competing dynamics that depend on their behaviour, and on their interaction with similar agents. We must consider economies in which: (1) the relevance of industries change across time and space and where firms in different industries behave differently and have different incentives; (2) the relation between industries also change constantly, affecting industrial dynamics, size, trade and transportation; (3) technical change is a complex process *per se*, which involves non measurable risks, investment, radical shifts and non reversible choices, and which determines future technical advances; (4) shifts in industries, industrial organisation and technical change determine radical changes in the demand for labour, and therefore in wages and income distribution; (5) changes in income distribution and technologies induce changes in consumption behaviour; (6) all above changes depend on how institutions change; (7) last but not least, climate change has heterogeneous impacts on each of

²⁶For a well reasoned and concise discussion about the limitations of CGE to model sustainability more in general see Scricciu (2007).

the above aspects of structural change, which is not predictable without considering how these impacts are distributed. For example, climate change may have an effect on migration through negative impacts on agricultural output. This in turn puts pressure on the political stability of immigration countries, which may further affect investment decisions, the labour market, as well as elections and theretofore climate policies.

Given the restrictive assumptions of IAM, CGE models, most SCM and the aggregate construction of EMK, to date only EABM seem able to take up the challenge of studying the interactions between several aspects of structural change, and with the environment. We have discussed a few examples that have investigated some of these interactions through changes in I/O relations, industrial dynamics, complex and uncertain technical change, technological transitions, employment, income distribution, demand preferences, heterogeneous feedbacks through sectoral shocks, and social interactions.

However, the EABM that have been developed so far exploit only some of the heterogeneity that is likely to influence climate change. Perhaps with the exception of technical change and industrial dynamics, these models tend to study different aspects of structural change separately. Ciarli et al. (2018) provide an example of how crucial aspects of structural change may be integrated in a unified growth model, but lack any reference on the relation with climate change.

The review could inform the next stage of evolutionary complex models, guiding the integration of aspects of structural change which are well developed in other modelling tradition, and in micro evolutionary models, in macro EABM. A better understanding of the complex interactions between structural and climate change might increase our ability to assess the relation between economic activity and climate change, improve the reliability of scenario analysis, and help design climate policies.

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A Tables

Sectors	IO	Aspects of structural change			
		Technical change	Employment	Demand	Institutions
Contribution to GHG	New intermediate sectors	Factor bias	Green jobs	Income distribution	Appropriation regimes
Innovative activity	I/O coefficients	Clean energy	Unemployment	Consumption preferences	Tech opportunities
Cost of abatement	Firm size	Radical innovations / tra- jectories	Distribution of wages	Time preferences	Access to resources
I/O relations	Industrial dynamics	Non linear and clustered process	Labour intensity		Governance
Dematerialisation	Geographic concentration	Uncertainties & unin- tended effects	Labour composition		Social interactions

Notes: We consider that a specific model considers one aspect of structural change if any of the listed changes is endogenous to the model (e.g. if a model has a fixed I/O structure, and none of the other aspects changes, we do not consider that it embeds features of structural change).

Table 1: *Aspects of structural change: main components interacting with climate change*

Models	Sectors	IO	Aspects of structural change			Demand	Institutions
			Technical change	Employment			
IAM	No: Aggregate & exogenous – no sectoral changes	No	Partial: Exogenous, LBD, induced TC, but aggregate	No		Limited: time preferences change with pollution	No (Policy experiments)
CGE	Partial: many sectors, with technical change that may affect GHG	No: I/O maps diversification, but static	Partial: Semi-exogenous, LBD, induced TC, but aggregate	No		Limited: change consumption patterns, not preferences	No (Policy experiments)
SCM	Yes	Yes, but only a couple of models	Yes, but only a couple of models	No		Limited: two populations	No (Policy experiments)
EMIK	Partial: labour composition	Not yet	No	Yes		Limited: wage distribution	No (Policy experiments)
EABM 1	Partial: weaker on the environmental effects	Limited: firm size & industrial dynamics	Largely Yes	Yes		Yes, although not developed	Partial: interaction & response to policies
EABM 2	No	Limited: mainly industrial dynamics	Yes	No		Yes	Partial: Evolution of power and tech. opportunities

Notes: IAM: integrated assessment models; CGE: computable general equilibrium models; SCM: structural change models; EMK: ecological macroeconomics (Keynesian); EABM 1: evolutionary and multi agent models (macro); EABM 2: evolutionary and multi agent models (innovations)

Table 2: **Aspects of structural change in different modelling traditions.** Some models are better equipped than others to capture the relation between aspects of structural change and environmental impact. In particular those that do not require a closed form solution in equilibrium.

Aspects of structural change	Models				
	IAM	CGE	SCM	EMK	EABM
Sectors					
Contribution to GHG		✓	✓	✓	✓
Innovative activity		✓	✓		✓
Cost of abatement					
I/O relations		✓ [†]	✓		✓
Dematerialisation			✓		
IO					
New intermediate sectors			✓		
I/O coefficients			✓	✓*	✓
Firm size					✓
Geographic concentration					
Industrial dynamics					✓
Technical change					
Factor saving	✓	✓	✓		✓
Clean energy	✓	✓	✓		✓
Radical innovations/trajectories			✓		✓
Non linear and clustered process					✓
Uncertainties & undesired effects					✓
Employment					
Green jobs					✓
Unemployment				✓	✓
Distribution of wages				✓*	✓
Labour intensity				✓*	✓
Labour composition			✓	✓	
Demand					
Income distribution			✓	✓*	✓
Consumption preferences		✓ ¹			✓
Time preferences	✓				
Institutions					
Appropriation regimes					
Tech opportunities					✓
Access to resources					
Governance					✓
Social interactions					✓

Notes: The table provides a bird's-eye view of which components of the six aspects of structural change considered in the paper. It should also be noted that models differ substantially (especially moving from SCM to the right): for a more specific discussion of some of the models the reader should refer to the relevant parts in Section 3. IAM: integrated assessment models; CGE: computable general equilibrium models; SCM: structural change models; EMK: ecological macroeconomics (Keynesian); EABM: evolutionary multi agent models (including micro models).

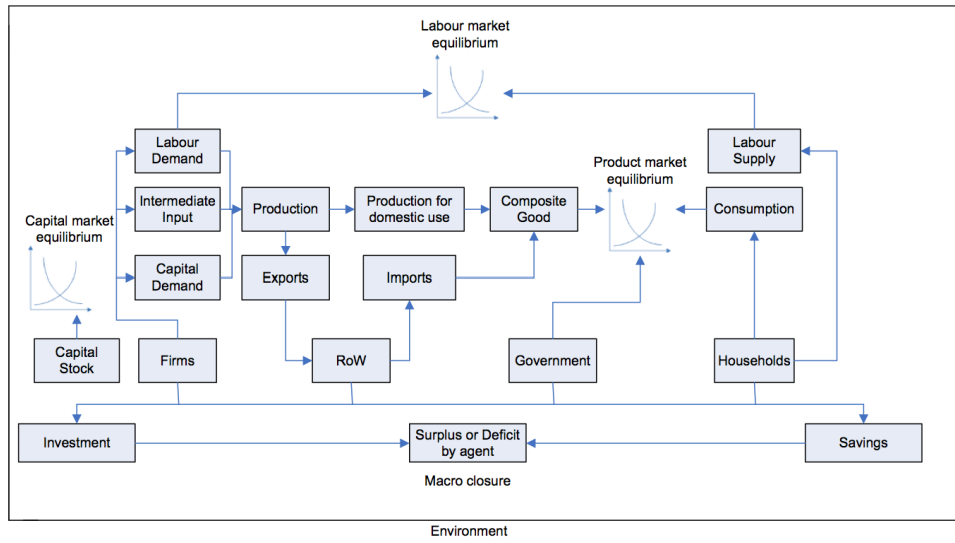
* indicates that the change is to be included in forthcoming models

[†] learning by doing

¹ changes in consumption patterns rather than preferences

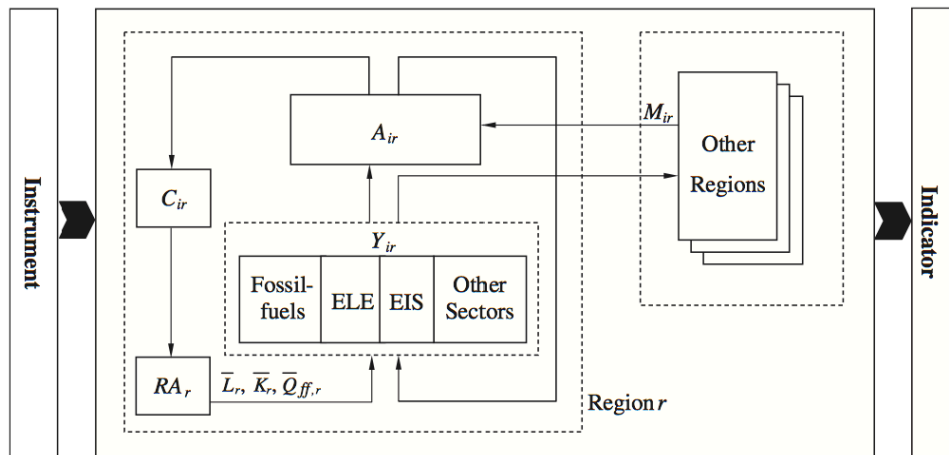
Table 3: *Components of structural change in different modelling traditions.*

B Figures



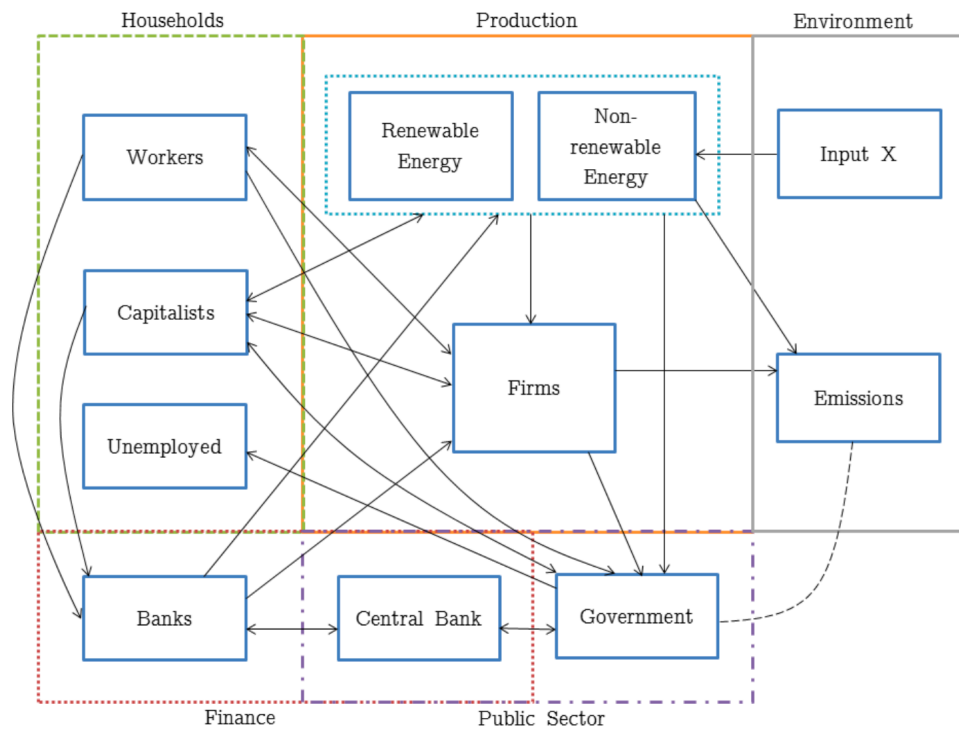
Notes. Source: Capros et al. (2013)

Figure 1: *The economic components and markets of a CGE model.*



Notes. Y_i is output of commodity i , using energy and non energy inputs; L , K , and Q are, respectively, labour, capital and fossil fuels inputs; output may be fossil fuels, electricity (ELE), energy intensive sectors (EIS) and other sectors; C_i is consumption of the representative agent RA of commodity i ; A_i are all domestic final and intermediate goods; and M_i are all imported final and intermediate goods. Source: Böhringer and Löschel (2006)

Figure 2: *Basic CGE structure*



Notes. Source: Jackson et al. (2016)

Figure 3: *Overall structure of a rich EMK model: ECOGRO*